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EXPERIMENTAL STUDY OF HYDRAULIC SYSTEMS
TRANSIENT RESPONSE CHARACTERISTICS

THESIS

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EXPERIMENTAL STUDY OF HYDRAULIC SYSTEMS TRANSIENT RESPONSE CHARACTERISTICS.

Thesis

Presented to the Faculty of the School of Engineering

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by

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Major, Israel Air Force

Graduate Aeronautical Engineering

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PREFACE

Hydraulic systems have a very important part in aircraft control systems. In order to design those systems more efficiently, the Air Force Aero-Propulsion Laboratory contracted with McDonnell Douglas Aircraft Corporation to develop a package of computer programs which predict hydraulic system responses. This thesis deals with a few aspects of one of these programs, "Hydraulic System Transient Response" (HYTRAN).

I wish to express my sincere appreciation to Dr. M. E. Franke who guided me in my study. This thesis would not have been possible without his able assistance and the sharing of his knowledge. I would also like to thank Mr. P. D. Lindquist, Mr. K. E. Binns (AFAPL), and Mr. R. Levek (McDonnell) for their big help in computer programming and hydraulic system operation.

My most sincere thanks to Mr. H. Lee, the technician for the hydraulic lab, and Mr. R. Esch, the instruments technician. Without their knowledge and patience I would not have any meaningful results.

Lastly I wish to thank my wife Anita and my family, whose understanding and patience let me accomplish this work.

Arie Zur

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ABSTRACT

The transient response characteristics of two laboratory hydraulic systems, consisting of a simple reservoir system and a pump system, were obtained both experimentally and by simulation with a computer program called "HYTRAN". Influence of various hydraulic components such as bends, filters and pulsation-dampening devices (Quincke-Tube) was determined by testing various experimental configurations and predicting the transient response with the "HYTRAN" computer program.

The correlation between computer and experimental results was quite good, especially in the simple reservoir system. Transient pressure peaks predicted by the computer program were within 20% of those obtained by experiment. The effect of sharp bends on system response was found to be negligible. Quincke-Tube influence and filter influence were found to attenuate both the pump ripple and the transient pressure peak. The transient response prediction of the "HYTRAN" program was found to be very sensitive to two input data parameters: the control valve closing time and the steady-state flow in the system.

EXPERIMENTAL STUDY OF HYDRAULIC SYSTEMS
TRANSIENT RESPONSE CHARACTERISTICS

I. INTRODUCTION

Background

The usual operation of hydraulic systems has many features that cause unsteady flow conditions. Valve opening and closing, ripple created by the pump, and the operation of actuators all cause unsteady flow conditions. Under these conditions the oil is accelerated in each direction. Because the oil has mass, it tends to resist any change in velocity. Because it is compressible, it can store and release energy like a spring.

Transient disturbances are usually the result of a rapid opening or a rapid closing of a valve. Of the two, the rapid closing of a valve is the more severe. This is because the velocity of flow is converted to a pressure rise above the steady state. This pressure rise is reflected back and forth along the tube at a velocity determined by the speed of sound in the fluid until the damping in the system attenuates the pressure pulse.

The hydraulic transient analysis computer program (HYTRAN) is intended for use by design engineers with an interest in the detailed performance of an aircraft hydraulic system. The program (Refs 1 and 2) simulates the complete system and calculates the value of all the state variables at specified points in the system. The program is a digital simulation process, which treats the fluid lines as distributed parameters. It applies the concepts of wave mechanics and includes the effects of nonlinear friction. The fluid line equations are solved with the help of the method of characteristics (Ref 3). The dynamic equations of the hydraulic system components are either algebraic or ordinary differential equations. These form the boundary conditions of the lines and are solved simultaneously with the associated line characteristic equations.

Objective

The objectives of this thesis were to:

1. Determine the transient response experimentally of a simple hydraulic system.

2. Predict the transient response with the HYTRAN computer program and correlate with the experimental results.

3. Determine experimentally and by computer the influence of a few simple hydraulic components on the transient response.

Scope

Tests were run with two simple systems. One consisted of a constant pressure reservoir as supply and a control valve; the other consisted of F-4 hydraulic pump and the same control valve. The reason for running the reservoir system was that it was a very simple system so it was easy to isolate and define any problems and complications. The reason for running the pump system was that its response resembled an actual aircraft hydraulic system more than the reservoir system. The transient response was induced by suddenly shutting the control valve and was recorded on a memory-oscilloscope. Different configurations were tested by replacing a straight line section in turn with a section with sharp bends, a section with a filter, and a section with a pulsation-dampening device called Quincke-Tube. Each configuration was simulated in the HYTRAN program and the computer prediction was compared to the experimental results.

II. EXPERIMENTAL EQUIPMENT AND INSTRUMENTATION

Tests were run with two simple systems. The main difference between them was the hydraulic power supply. One used a constant pressure reservoir, and the other a hydraulic pump.

Reservoir System

General Description. The reservoir system is shown in Figs 1 and 2. The power supply was a nitrogen gas bottle which pressurized the reservoir. The receiver was kept at atmospheric pressure. The control valve was a Moog servovalve no. 32S020 which was chosen for its quick response (5.5 msec closing time at 3000 psia).

Stainless steel type 321 lines, 3/8" diameter and 126" long, with MIL-H-5606 hydraulic fluid were used.

Instrumentation

Pressure changes were measured by strain-gage type pressure transducers located at positions shown in Fig 1. The outputs of the transducers were amplified and recorded on a memory oscilloscope. Photographs of the oscilloscope traces were taken with a polaroid camera. The oscilloscope was triggered by the switch of the control valve.

Flow was measured by a frequency-flowmeter and was recorded on an oscillograph-recorder. Pressure P2 (as a cross-check) and P6 (for checking the supply pressure) were also recorded.

Temperature was measured by Iron-Constantan thermocouples at the two points shown in Fig 1 (T1, T2).

The instrumentation set-up is shown Fig 3.

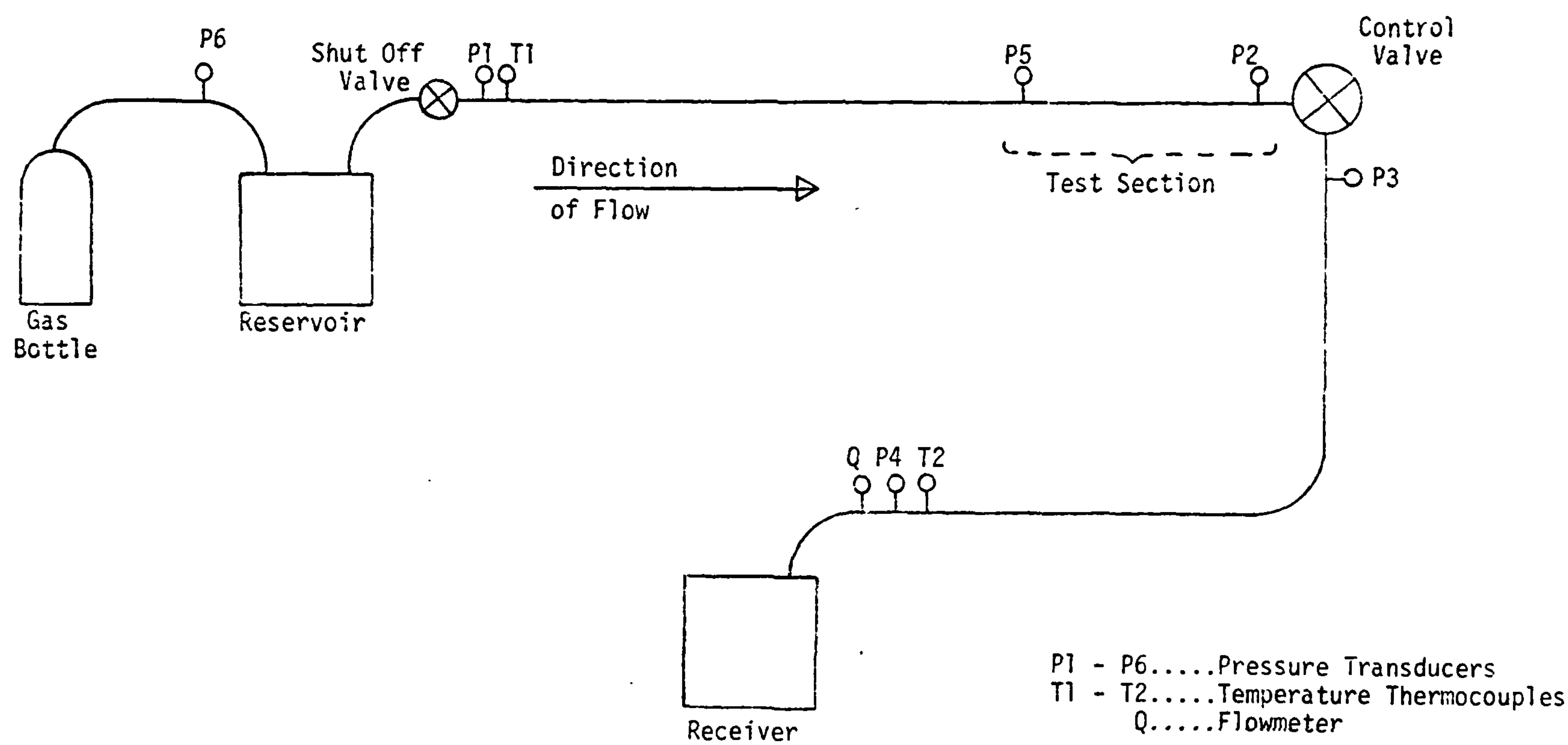


Fig 1. Schematic of Reservoir System

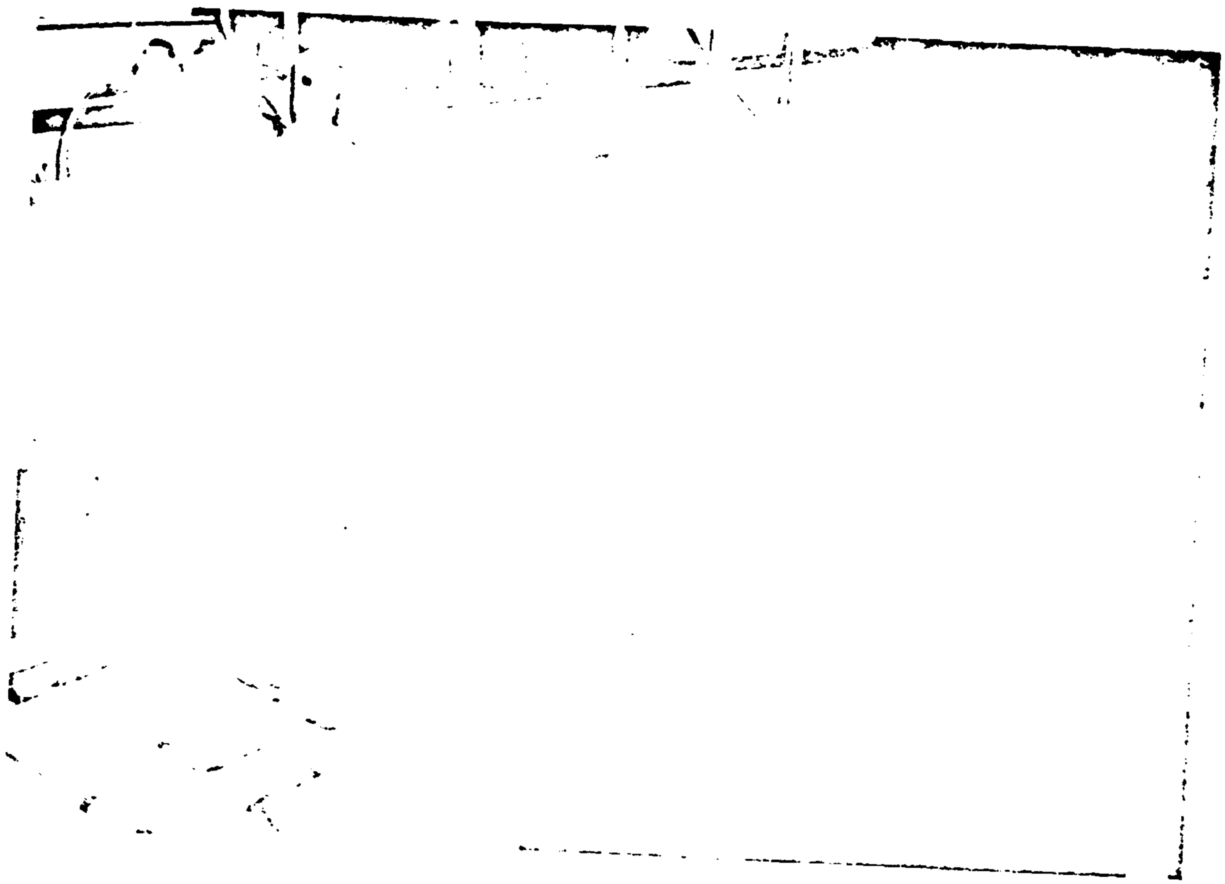


Fig 2. Photograph of Reservoir System

Configurations

Tests were run on various system configurations. The straight line section shown in Fig 4 was replaced in turn with the filter section and sharp bends shown in Fig 4, and then by the so-called Quincke-Tube shown in Fig 5.

The sharp bends were formed by using 90 degrees fittings. The filter was MIL STD AN-6234 with element AN 6234-3.

The Quincke-Tube is a pulsation-dampening device. Pressure pulses in hydraulic systems are caused by the operation of hydraulic pumps. The attenuation of those pressure pulses is obtained by adding a by-pass line which differs by half-wavelength from the main line length (Ref 4). The pressure pulse, travelling an extra half wavelength through the by-pass, changes its phase angle by 180^0, and becomes opposite in its sign with respect to the pulse travelling through the main line. Superimposing the two pulses together, they cancel each other. If a whole wavelength by-pass is used, the pressure pulses should be amplified instead of attenuated. For this experiment the Quincke-Tube was calculated for the pump speed of 3750 RPM (562 H_z) and was run in two configurations: the short Quincke-Tube was designed as a half wavelength device, whereas the long Quincke-Tube was designed twice as long.

Each configuration was modeled in the HYTRAN program. An example of program input for the filter configuration is shown in the Appendix.

Test Procedures

The test procedures in the reservoir system were as follows:

1. Pressurize the reservoir to a desired constant pressure.

2. Open the control valve and let the flow rate steady itself.

3. Shut the control valve and photograph the transient response trace on the oscilloscope.

Pump System

General Description. The second system used an F-4 hydraulic pump (No. 55001) instead of the reservoir and the former control valve (see Fig 6). The pump was run at constant speed of 3750 RPM which is its speed at cruising flight.

A small cooling system was added to the reservoir because the rate of fluid heating by the pump was too high. This was not modeled in the program because it was proved experimentally (by disconnecting it from the reservoir) that it did not influence the response.

A load valve (installed downstream of the control valve) was used to control the desired steady flow rate in the system.

Instrumentation. The same instrumentation that had been used for the reservoir system was used for the pump system. Readings were taken at the points shown in Fig 6.

Configurations. The same configurations that had been used for the reservoir system were used for the pump system (Figs 4 and 5), except that another filter (that would withstand 3000 psi pressure) was used in the third configuration. This was an MS 28895-12 filter.

An example of program input for the Quincke-Tube configuration in the pump system is shown in the Appendix.

Test Procedures. The test procedures in the pump system were as follows:

1. Operate the pump at constant speed.

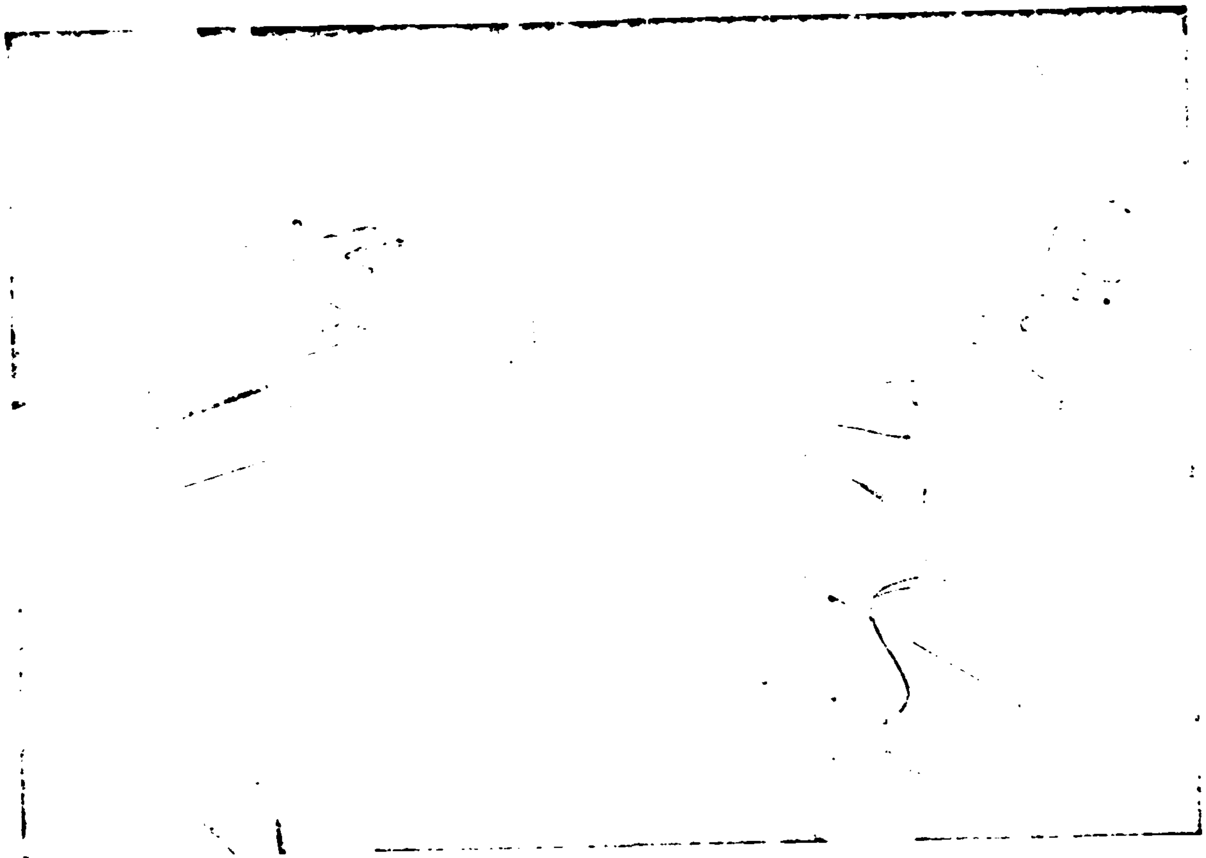


Fig 3. Photograph of Instrumentation Set-Up

Straight Line

Filter

Sharp Bends

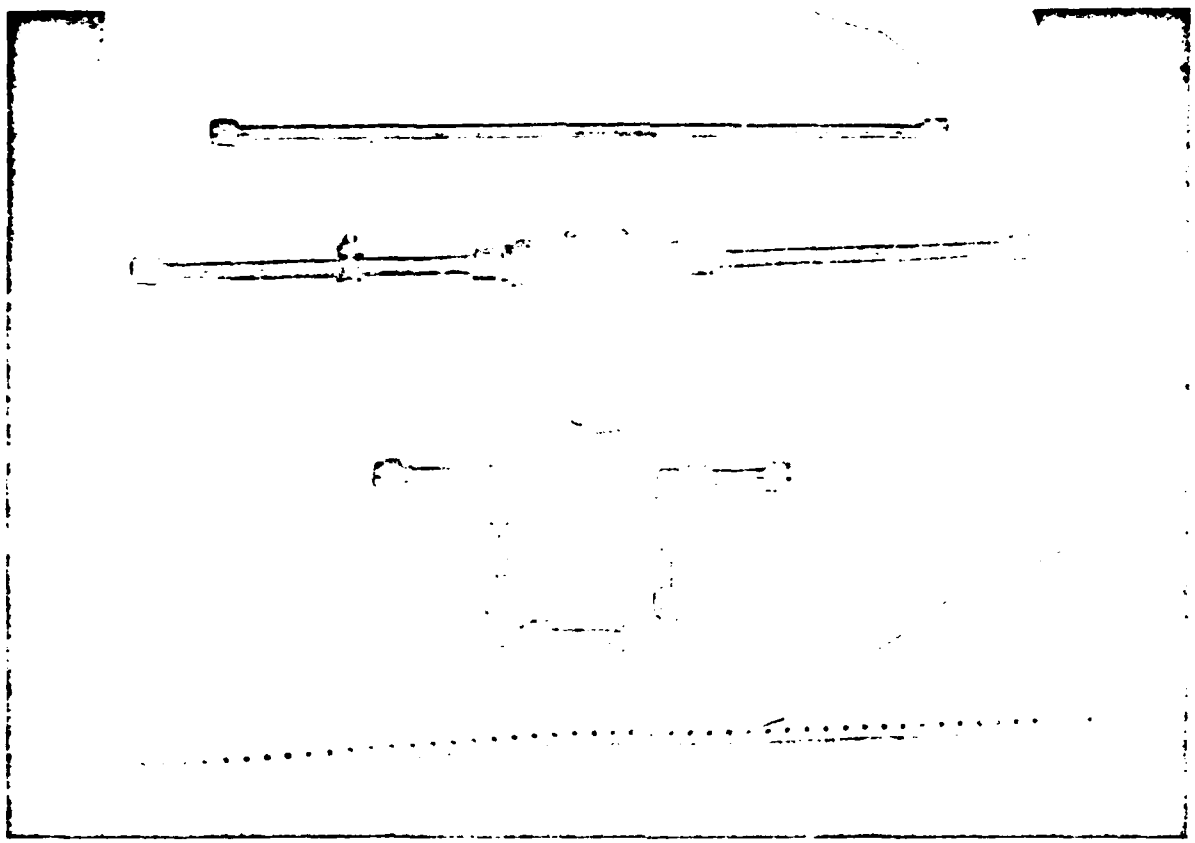


Fig 4. Test Configurations

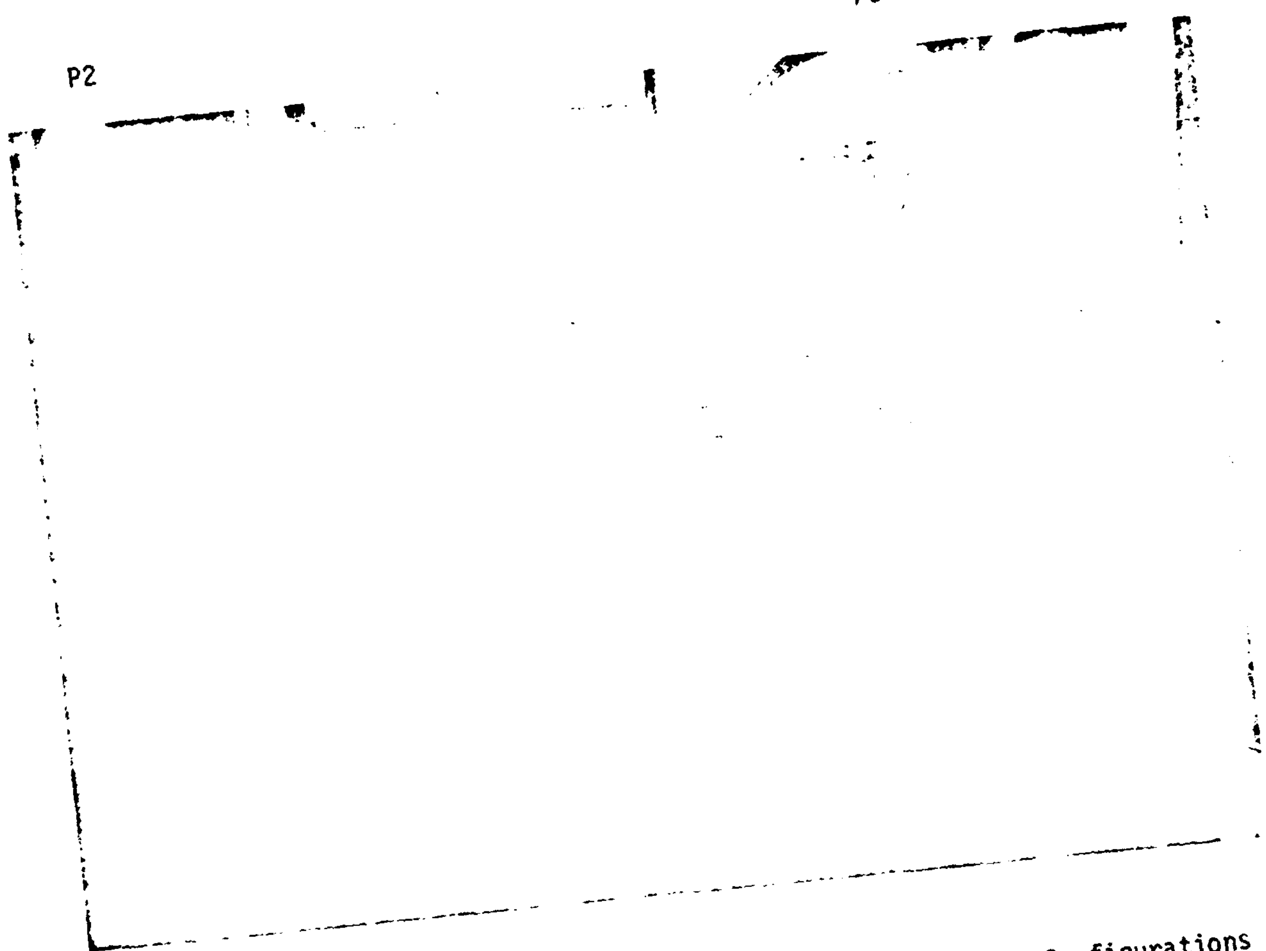


Fig 5. Test Section In Reservoir System With Quincke-Tube Configurations

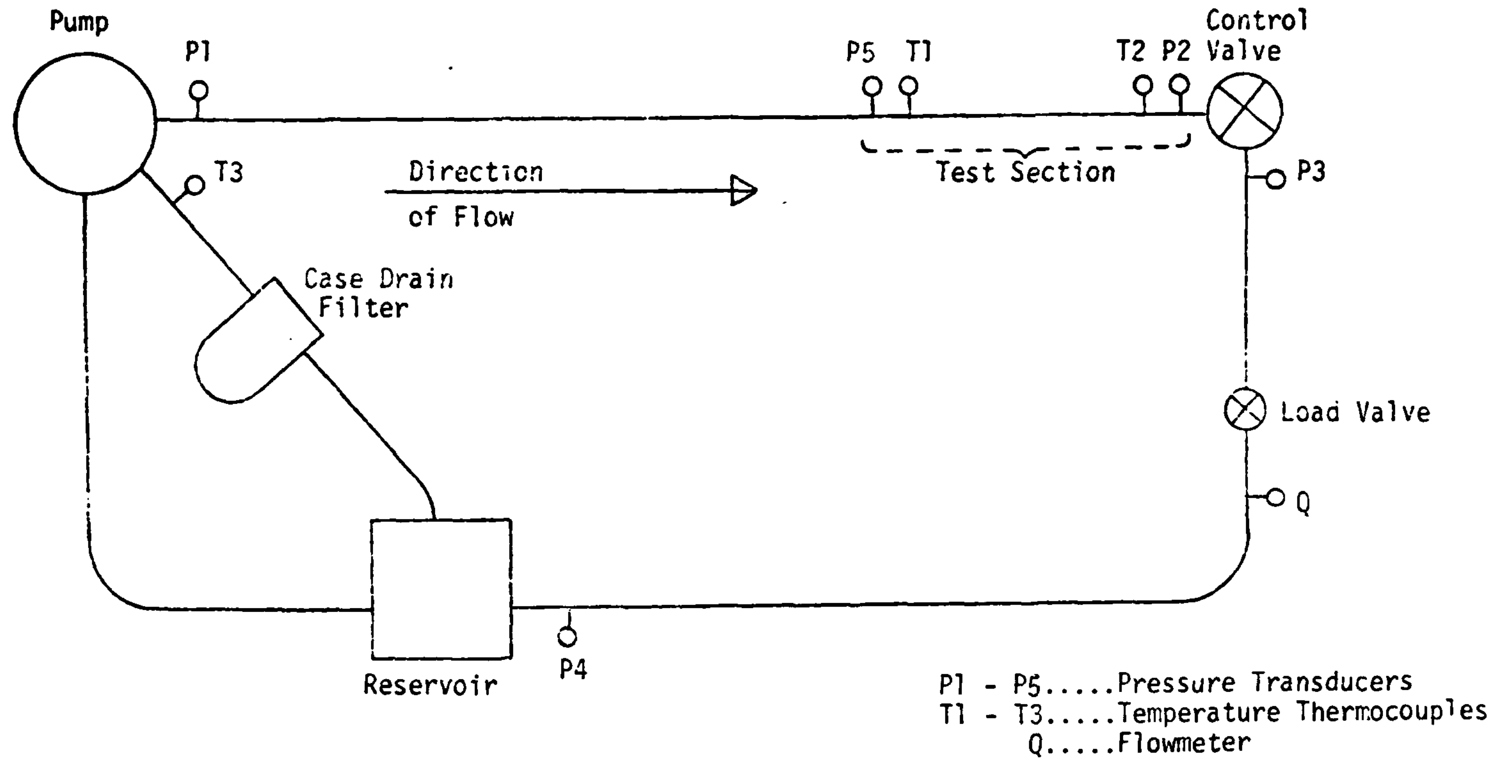


Fig 6. Schematic of Pump System

2. Open the control valve and let the flow rate steady itself.

3. Shut the control valve and photograph the transient response trace on the oscilloscope.

III. RESULTS AND DISCUSSIONS

Correlation Between Computer and Experimental Results

The HYTRAN computer program predictions were correlated with the experimental results for all configurations. About 200 experimental runs were made, in which transient responses were recorded at the various points of the two systems (Figs 1 and 6). Some preliminary runs were made to reduce operating problems in the system and instruments (like steadying the supply pressure). About 1000 computer runs were required in order to get a good match of the results or an average of 70 computer runs for each tested configuration. The match of results was obtained by matching the steady state flow rate in the experiment with the computer program and determining the closing time of the control valve from the pressure transducer downstream of the control valve (P3 in Figs 1 and 6). The results of the correlation are summed up in Tables 1 and 2, for the same point in all systems - just upstream of the control valve (P2 in Figs 1 and 6), where the highest pressure peaks in the system occur. Those high transient pressure peaks can cause failure in hydraulic lines that are not designed for those pressures.

The prediction error for the transient pressure peaks was calculated by this formula:

$$\text{Prediction Error (\%)} = \left\{ \frac{\text{(Computer Result)}}{\text{(Experimental Result)}} - 1 \right\} \times 100$$

The results show a very good match and small error in transient pressure peak prediction. As an example for good correlation the configuration of reservoir system with filter (at 165 PSIA) was chosen.

Configuration	Supply Pressure (PSIA)	Experimental Results			"HYTRAN" Predictions			Pressure Prediction Error (%)
		Run No.	Flow (GPM)	Pressure Peak (PSIA)	Run No.	Flow (GPM)	Pressure Peak (PSIA)	
Straight Line	165	73	4.6	505	714	4.59	480	-5
	505	79	8.25	1255	715	8.28	1300	+4
Sharp Bends	165	62	4.35	515	806	4.35	440	-15
	505	66	7.95	1245	802	7.95	1320	+6
Filter	165	97	4.45	435	905	4.48	440	+1
	505	102	8.1	1135	909	8.10	1320	+16
Quincke Tube (Short)	165	116	4.45	525	1101	4.44	490	- 7
	505	111	8.0	1275	1107	8.00	1420	+11
Quincke Tube (Long)	165	134	4.45	515	1115	4.44	500	-3
	505	143	8.0	1275	1116	7.99	1460	+15

TABLE 1. Correlation Between Experimental Results and "HYTRAN" Computer Program Predictions. Reservoir System, Point P2.

Configuration	Experimental Results			"HYTRAN" Predictions			Pressure Prediction Error (%)
	Run No.	Flow (GPM)	Pressure Peak (PSIA)	Run No.	Flow (GPM)	Pressure Peak (PSIA)	
Straight Line	170	8.0	4300	2002	8.03	4600	+7
Sharp Bends	181	8.0	4200	2202	7.97	4600	+10
Filter	186	8.0	3800	2302	8.03	4340	+14
Quincke Tube (Short)	155	8.0	4050	2102	8.01	4700	+16
Quincke Tube (Long)	152	8.0	4000	2152	8.01	4800	+20

TABLE 2. Correlation Between Experimental Results and "HYTRAN" Computer Program Predictions. Pump System, Point P2.

Fig 7 shows the HYTRAN computer program prediction of the transient response. Fig 8 shows the experimental result for the same configuration. Fig 9 shows the correlation between those two. This configuration gives a very good match (1% error) in the amplitude of the transient pressure peak, but there is a shifting in the time scale, which is not so important as the pressure and will be discussed later (in the error estimation section).

Correlations between experimental and computer results for other configurations are shown in Figs 10 and 11.

In order to get good computer simulations, the input data as defined in the program user manual (Ref 1) should be as accurate as possible. There are a few input parameters to which the HYTRAN program is very sensitive, and great care should be taken in defining those parameters. Two of those parameters are control valve closing time and the steady state flow rate in the system. The flow is calculated at the first section of the program by taking all the parameters that influence the system's impedance (lines diameters and lengths, orifices diameters and coefficients, etc.). This sensitivity was determined by running successive computer runs and changing only one parameter. An increase of 100% in flow-rate caused an increase of 50% in transient pressure peak. An increase of 50% in control valve closing time caused a decrease of 40% in transient pressure peak.

It is very difficult to find the required input data parameters of hydraulic components (such as valves, filters, pumps) for the HYTRAN computer program. Some of them are found in vendor's catalogs, and some require carefully instrumented experiments to evaluate them. Some

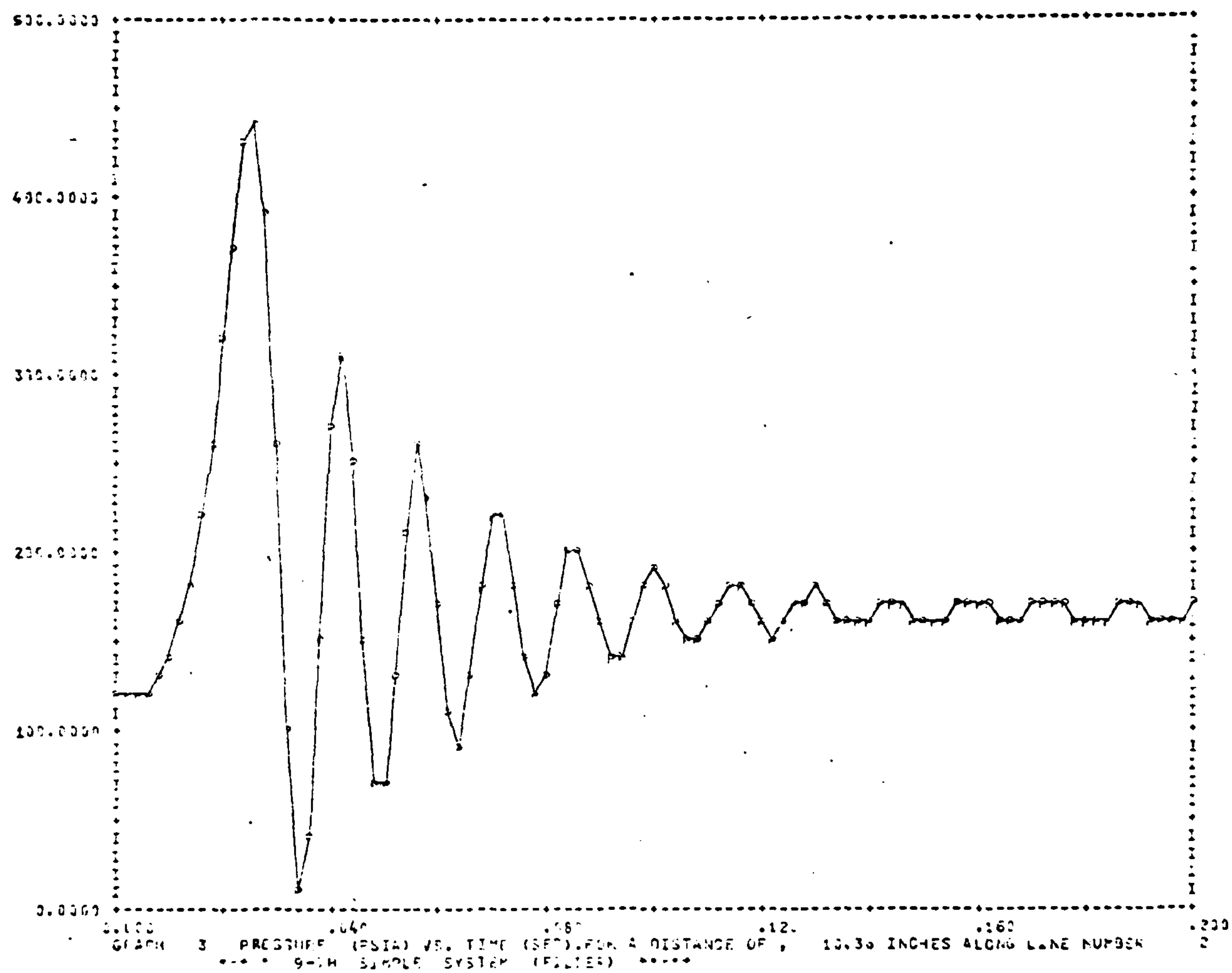


Fig. 7. Example of Computer Output Plot .
Reservoir System, Filter Configuration, 165 PSIA

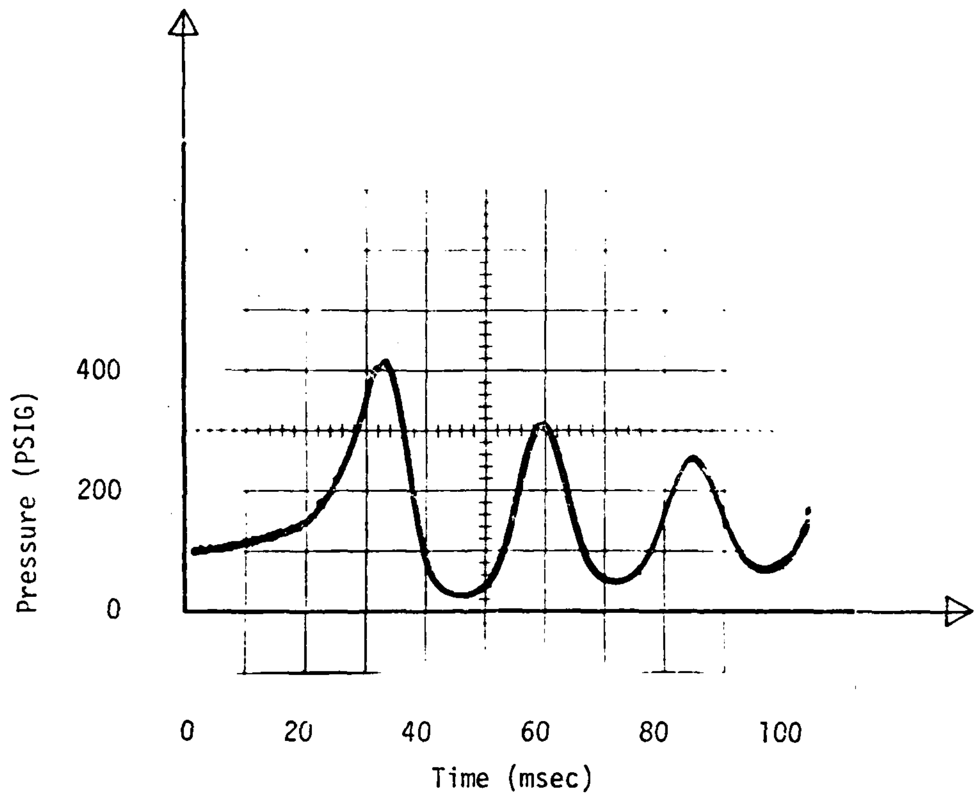


Fig 8. Example of Experimental Result. Reservoir System, Filter Configuration, 165 PSIA.

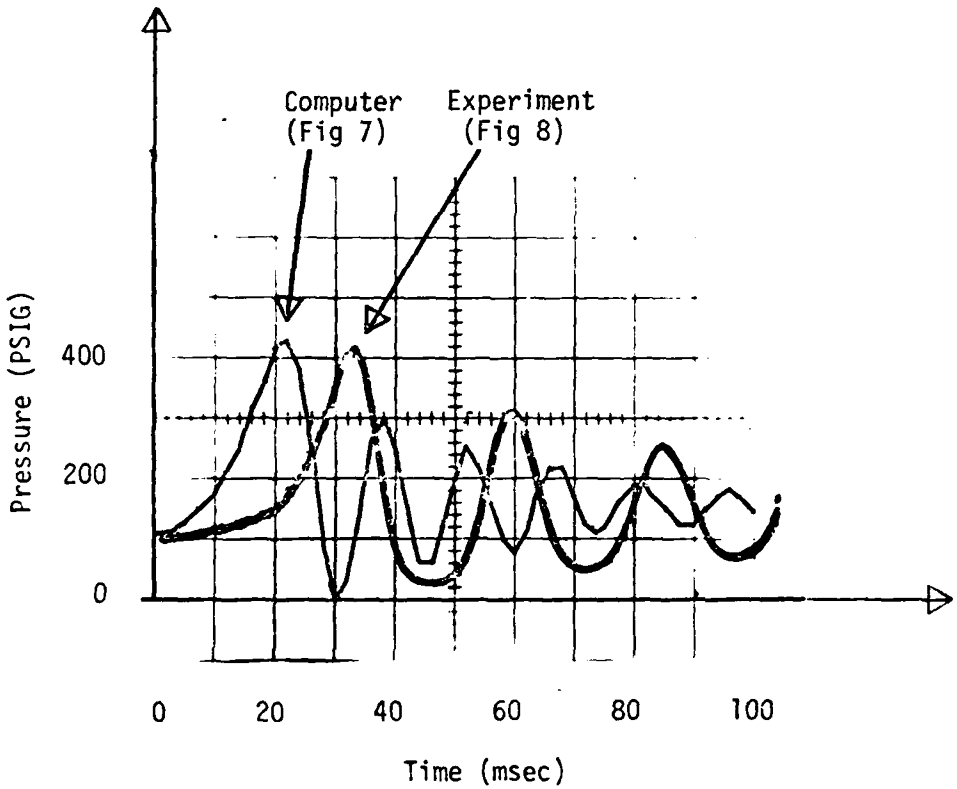


Fig 9. Correlation Between Experimental and Computer Results. Reservoir System, Filter Configuration, 165 PSIA.

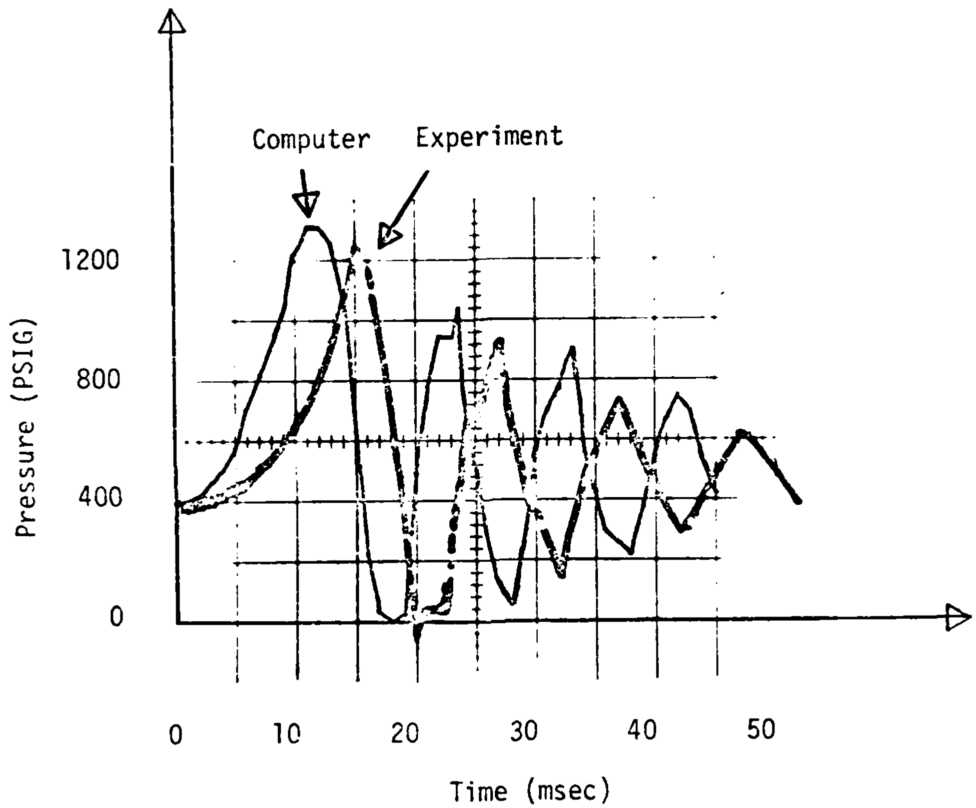


Fig 10. Correlation Between Experimental and Computer Results.
Reservoir System, Straight Line Configuration, 505 PSIA.

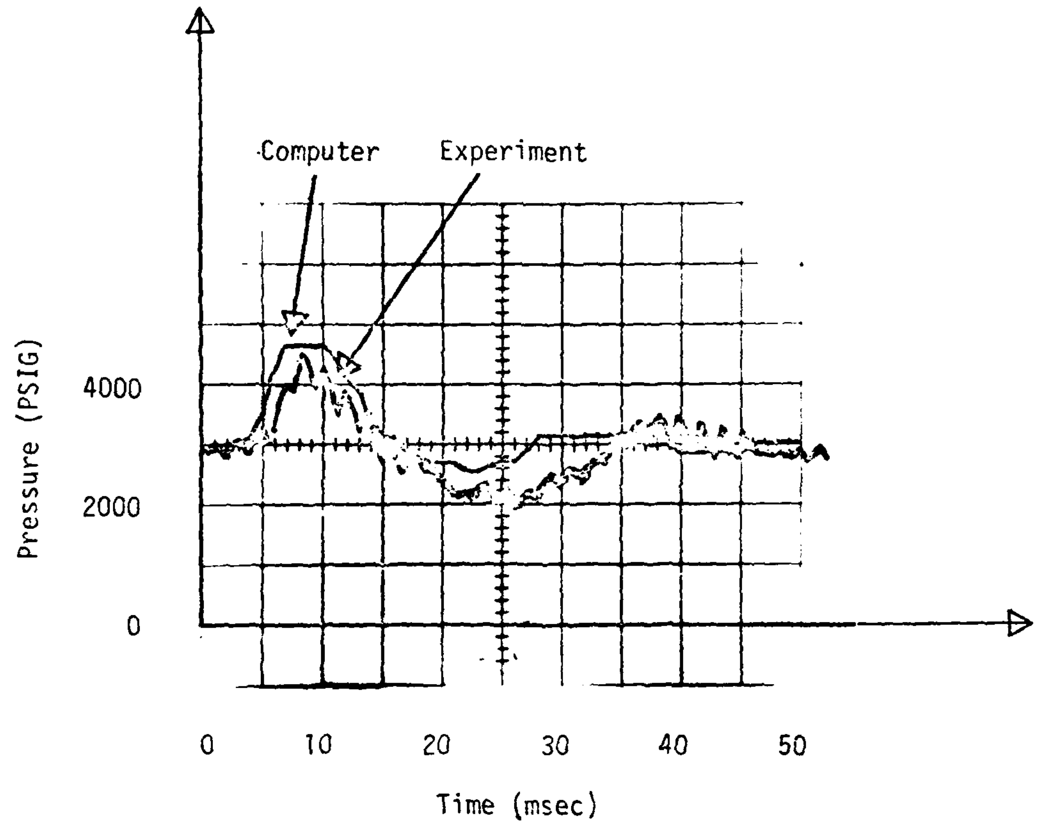


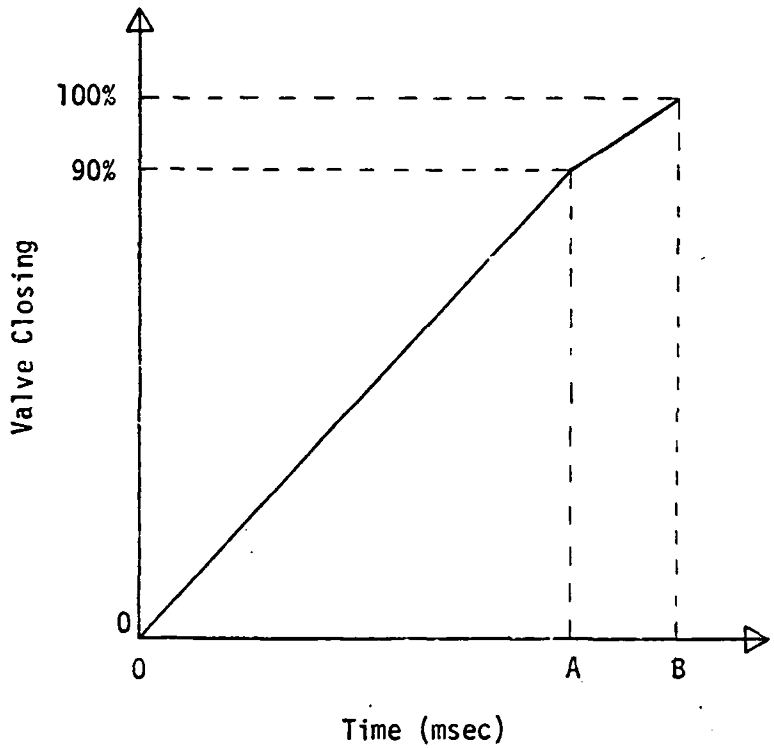
Fig 11. Correlation Between Experimental and Computer Results. Pump System, Straight Line Configuration.

parameters were obtained by discussions with vendors. Special care should be taken when some of these parameters are not constant when running the system on different conditions. For example: In the servo-valve that was used in the experiment, the closing time depends very much on the pressure in the system. This change is shown in Fig 12. The data for this curve did not exist in the catalog of the valve and was obtained by discussion with the vendor. It was verified experimentally by tracing the transient response at the pressure transducer downstream of the control valve (P3 in Figs 1 and 6).

The experimental results were also compared with a basic waterhammer computer program (Ref 3). For the reservoir system straight-line configuration (165 PSIA) this program gave a transient pressure peak of 575 PSIA (Fig 13), which deviated by 14% from the experimental result of 505 PSIA, whereas the HYTRAN program predicted a transient pressure peak of 480 PSIA which was within 5% of the experiment. The HYTRAN program is more accurate maybe because its mathematical model includes the effects of nonlinear friction .

Effects of Sharp Bends

The sharp-bends configuration was compared to the straight-line configuration by running the systems under the same test conditions. The results are shown in Figs 14 and 15. The pressure transients were apparently the same and the differences of the first peaks were so small that they were within the order of readability error of the instruments. Since the responses (Figs 14 and 15) were much the same, it appears the sharp bends do not cause any change on the second peaks. This result



Supply Pressure (PSIA)	A (msec)	B (msec)
165	19.2	23
505	11	13.2
2900	4.5	5.5

Fig. 12. Valve Closing Curve

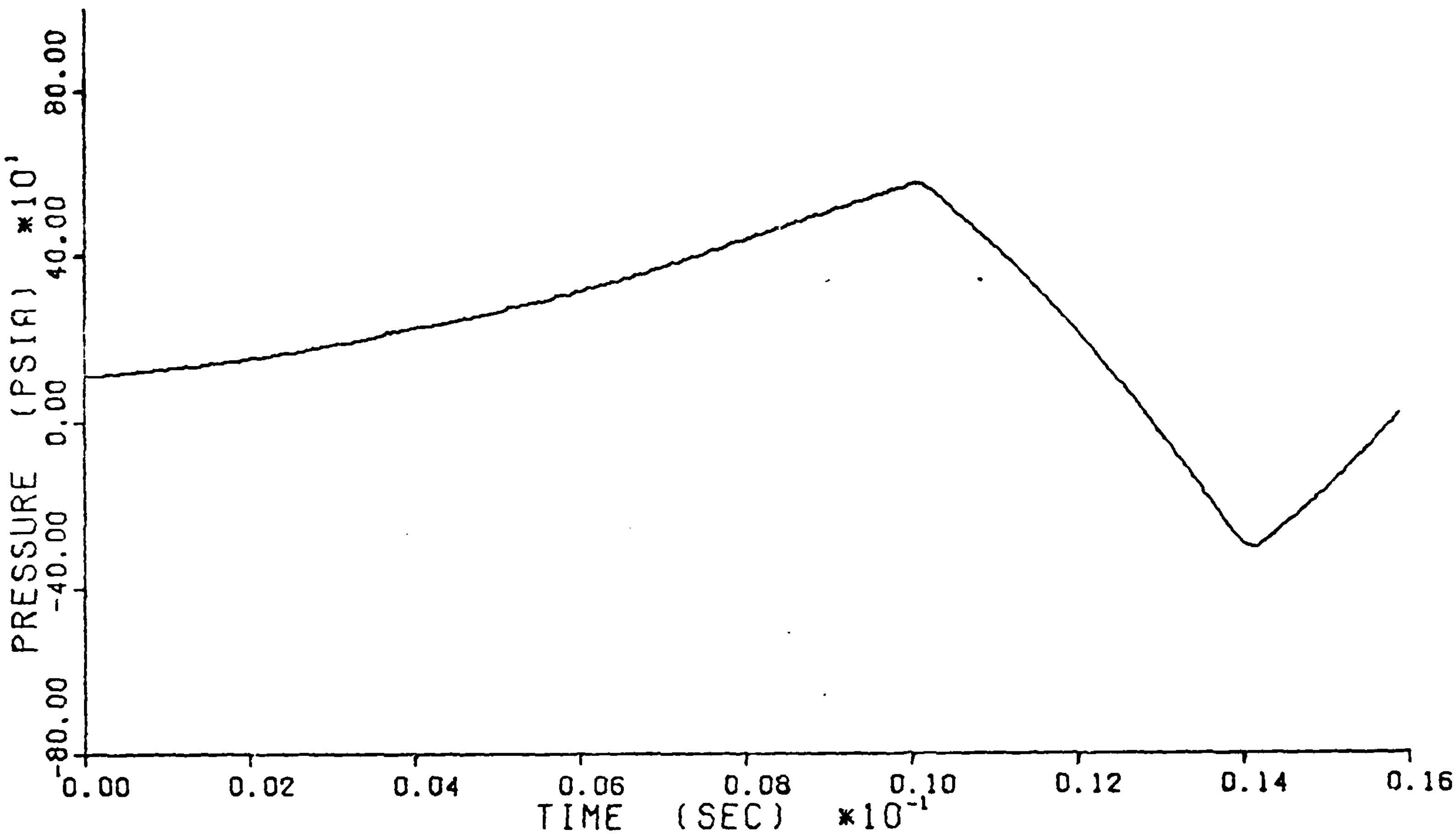


Fig. 13. Basic Waterhammer Program for Reservoir System, Straight-Line Configuration, 165 PSIA.

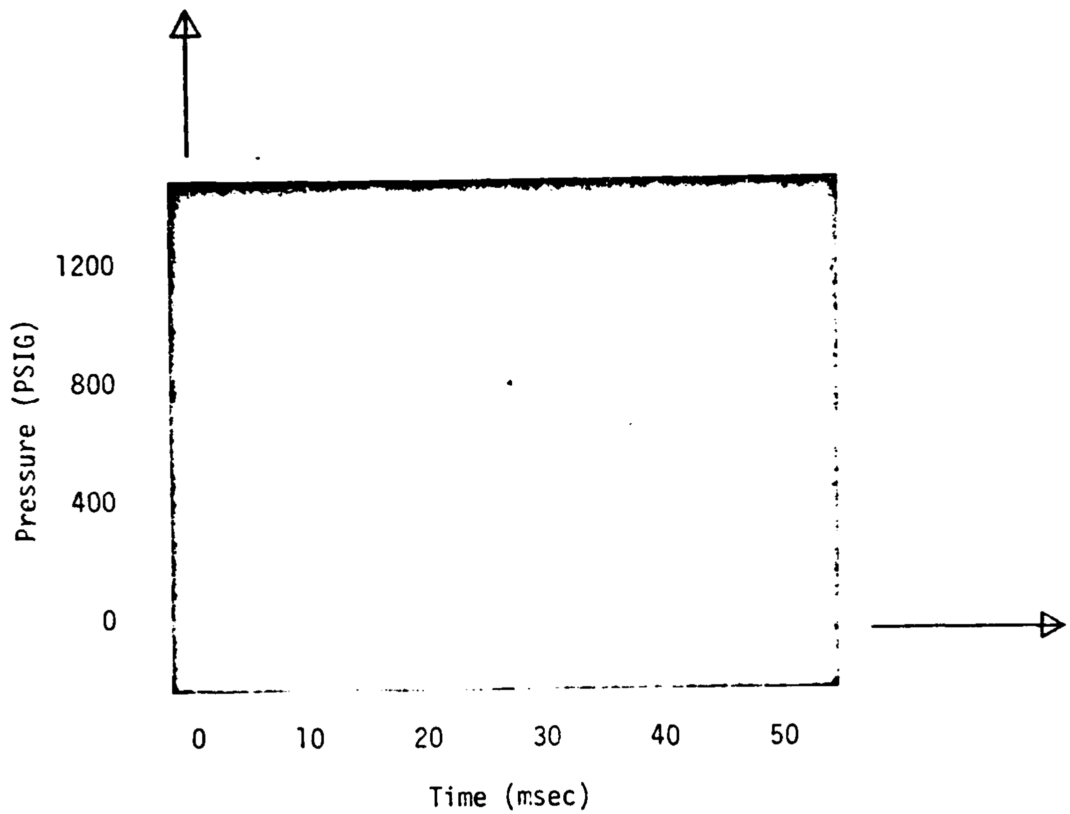


Fig 14. Transient Response, Reservoir System, Straight Line Configuration, 505 PSIA

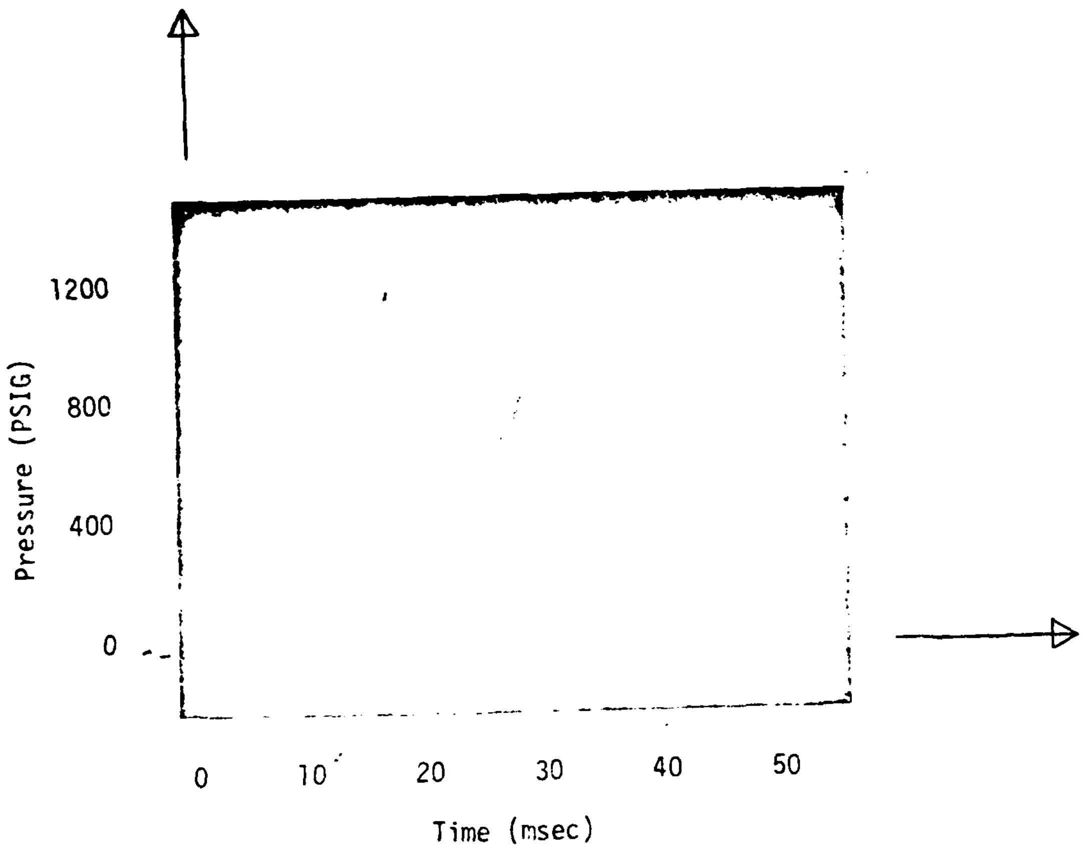


Fig 15. Transient Response, Reservoir System, Sharp Bends Configuration, 505 PSIA.

does not agree with a study made by Philips (Ref 5), who showed that the transmission of a waterhammer-type wave through a typical elbow is about 85% in pressure magnitude. However, there is nothing in the transient response shown in Fig 15 to verify the transmission and reflection coefficients discussed by Philips.

Effects of Filter

The filter attenuated the transient pressure peak in both systems. In the reservoir system the attenuation was 14% and in the pump system 12%. Figs 16 and 17 show that, although the first two pressure peaks in the filter configuration were attenuated, it took longer time for the whole transient response to dampen. The reason for this longer dampening time was probably the filter's volume which caused the pressure pulse to take longer rising time in the volume until it was reflected back to the control valve. The HYTRAN prediction of the transient response was very similar to the experimental result (Fig 9). In the pump system the filter attenuated the pump pressure ripple as well as the transient pressure peak (Figs 18, 19), but that ripple appeared again during the transient. The attenuations (of transients and ripple) caused by the filter are mainly due to its volume, which dampens the pressure changes by adding capacitance to the system's impedance.

Effects of Quincke-Tube

The Quincke-Tube configurations (both short and long) made no change in the reservoir system on the first transient peak (Figs 14 and 20). However, there were some changes in the second peaks, which are much less important than the first.

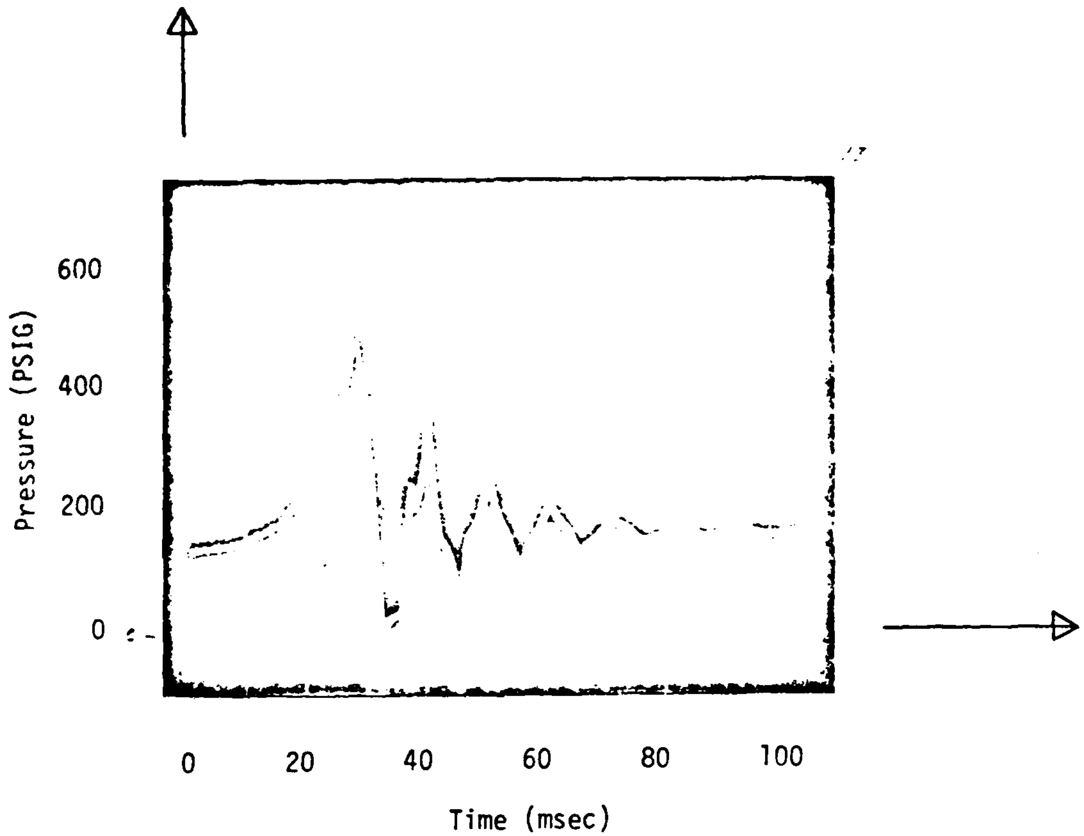


Fig 16. Transient Response, Reservoir System, Straight Line Configuration, 165 PSIA

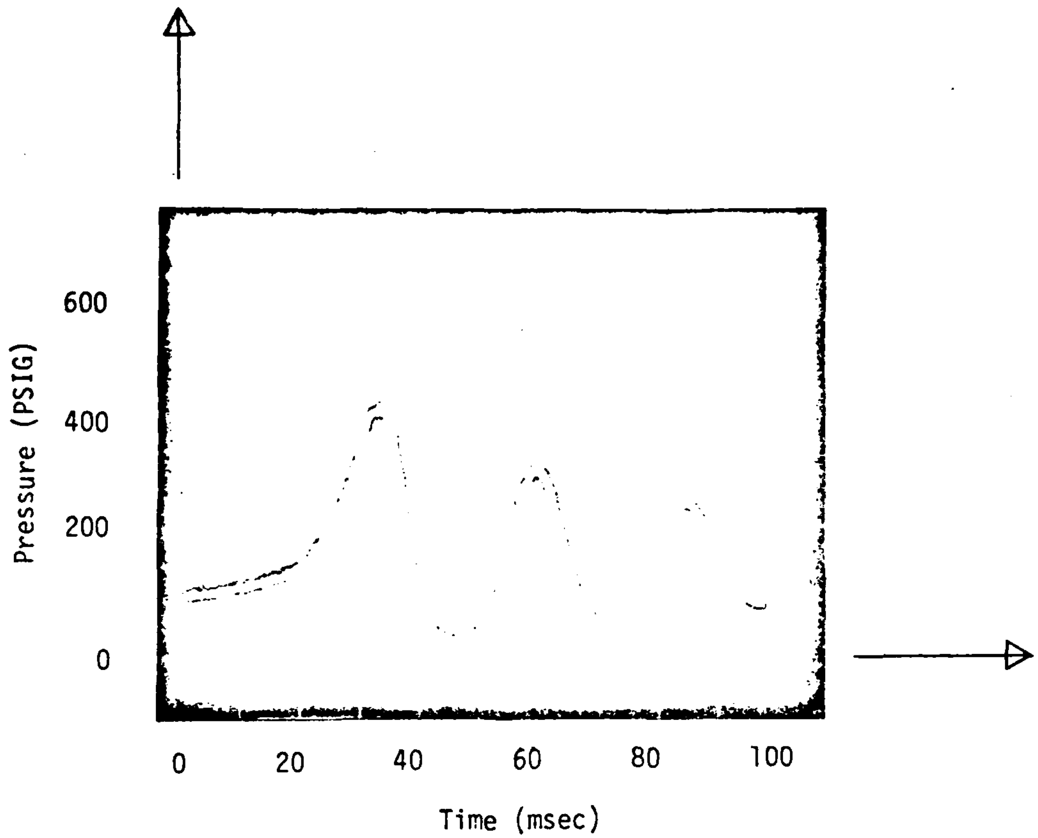


Fig 17. Transient Response, Reservoir System Filter Configuration, 165 PSIA

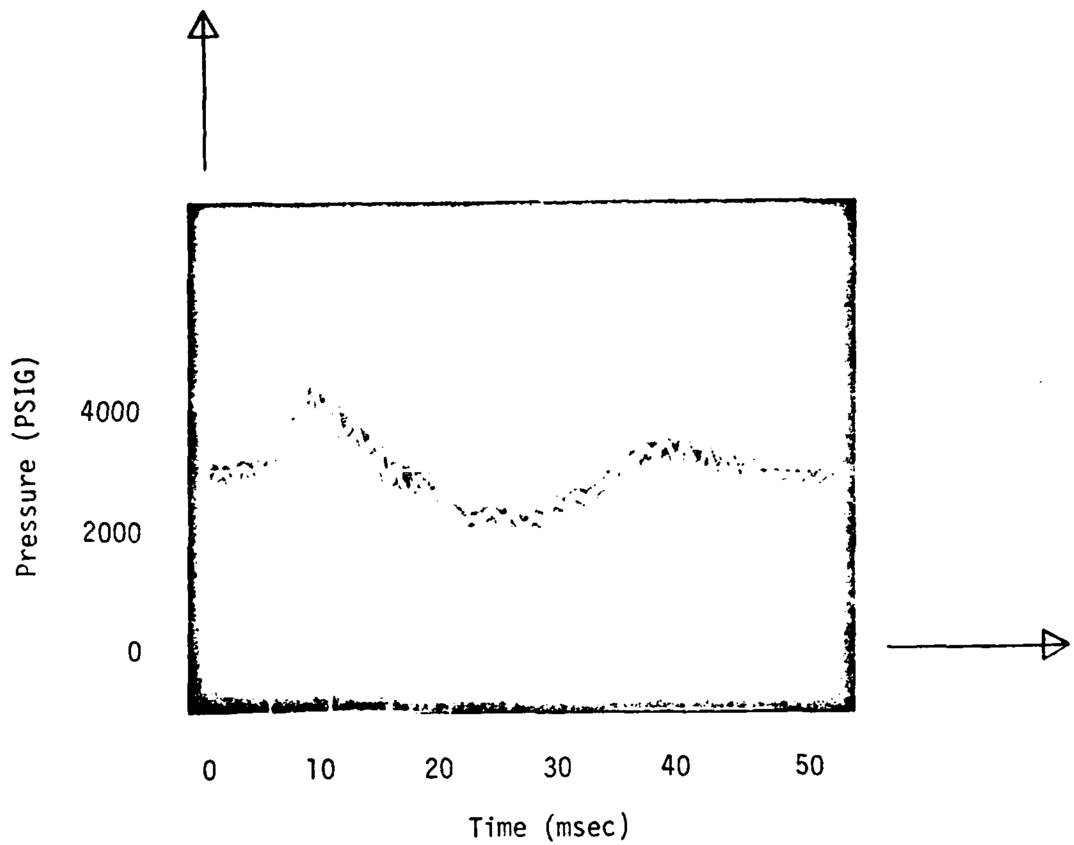


Fig 18. Transient Response, Pump System, Straight Line Configuration

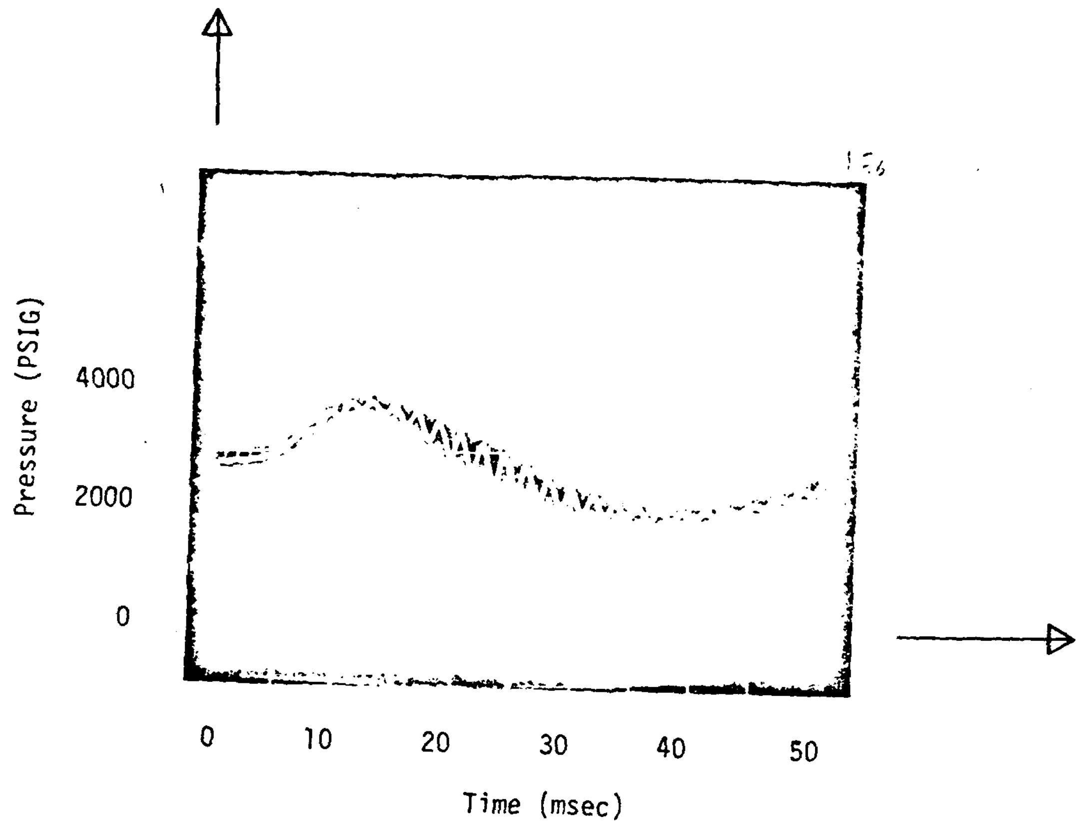


Fig 19. Transient Response, Pump System, Filter Configuration

In the pump system two phenomena were caused by the Quincke-Tube. Both short and long tubes attenuated the transient pressure peak (Figs 18, 21 and 22). A strong dampening of the pump pressure ripple can be seen by comparing the pressure transient downstream of the short Quincke-Tube (Fig 22), and the pressure transient upstream of the Quincke-Tube (Fig 23). In the long Quincke-Tube configuration the pump ripple was the same as in the straight line configuration (Figs 18 and 21).

Although the Quincke-Tube (short or half wavelength) was designed to dampen the pump ripple (for frequency of 562 H_Z or 3750 RPM) and accomplished it quite well, it also attenuated the transient pressure peak which was at another frequency (20 H_Z).

Error Estimation

The errors in the experimental results came mainly from the readability and accuracy limitations of the oscilloscope. More accurate measurements would have been obtained if the transient response were recorded on a magnetic tape and plotted on larger scale plotter. The readability was 1/20 cm, which was 50 PSI in the pump system and 10 PSI in the reservoir system. Nevertheless, the repeatability in the experiments was very good when all conditions were kept the same. In the pump system, the pump pressure ripple was superimposed on the transient response, which made it difficult to read. Improvement in transient readings can be obtained by dampening the ripple with a filter.

The readability on the oscillograph that recorded the flow was 0.05 GPM, and on the thermocouples 0.5^{o}F.

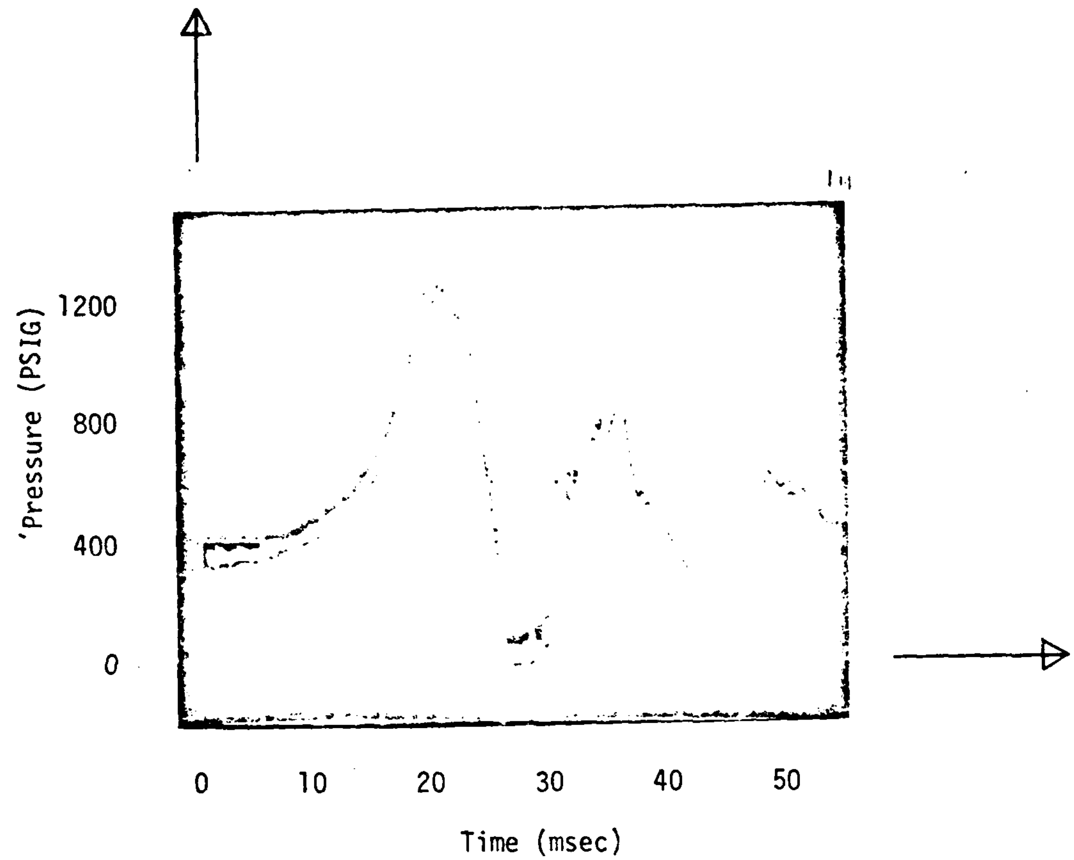


Fig 20. Transient Response, Reservoir System, Quincke-Tube (Short) Configuration, 505 PSIA.

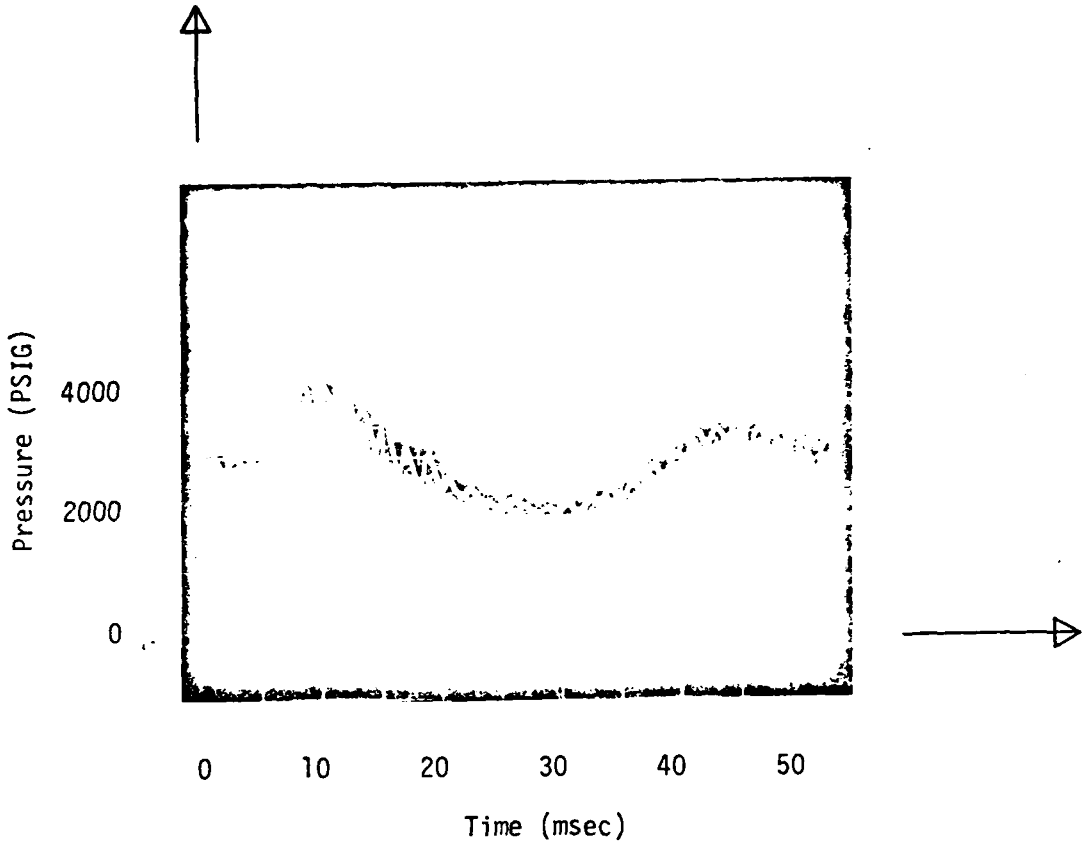


Fig 21. Transient Response, Pump System, Quincke-Tube (Long) Configuration

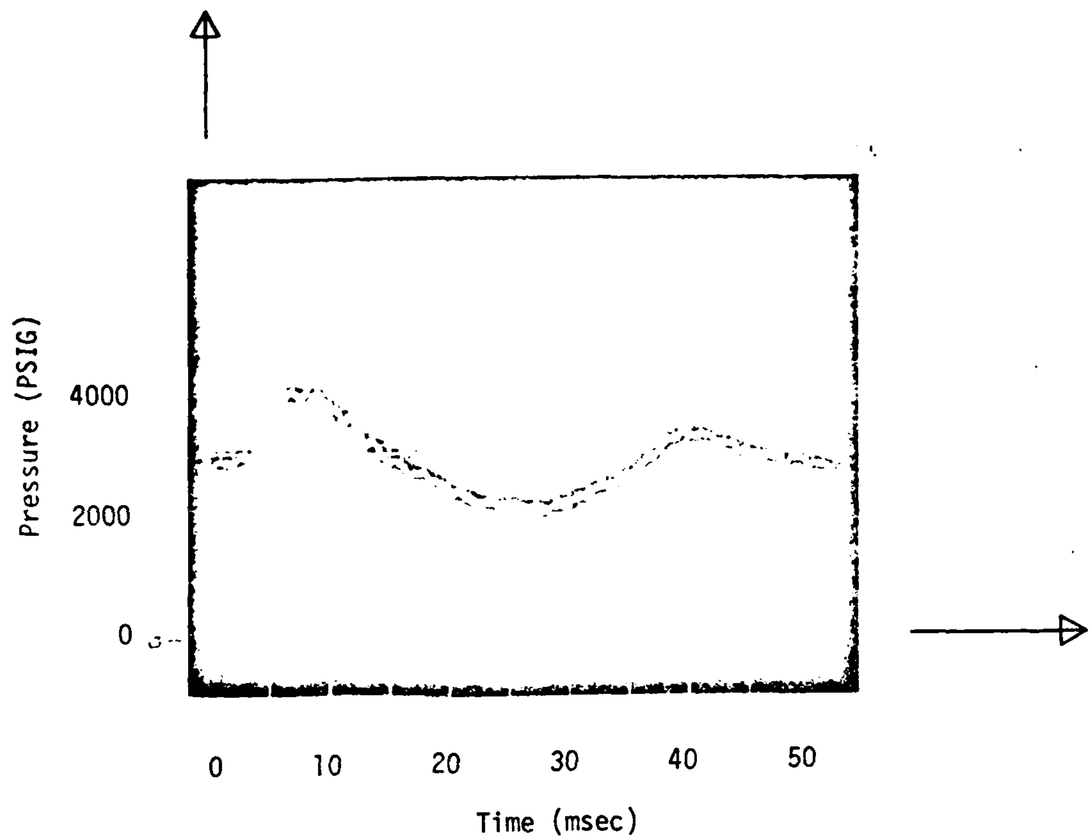


Fig 22. Transient Response, Pump System,
Quincke-Tube (Short) Configuration, Taken at Point P2

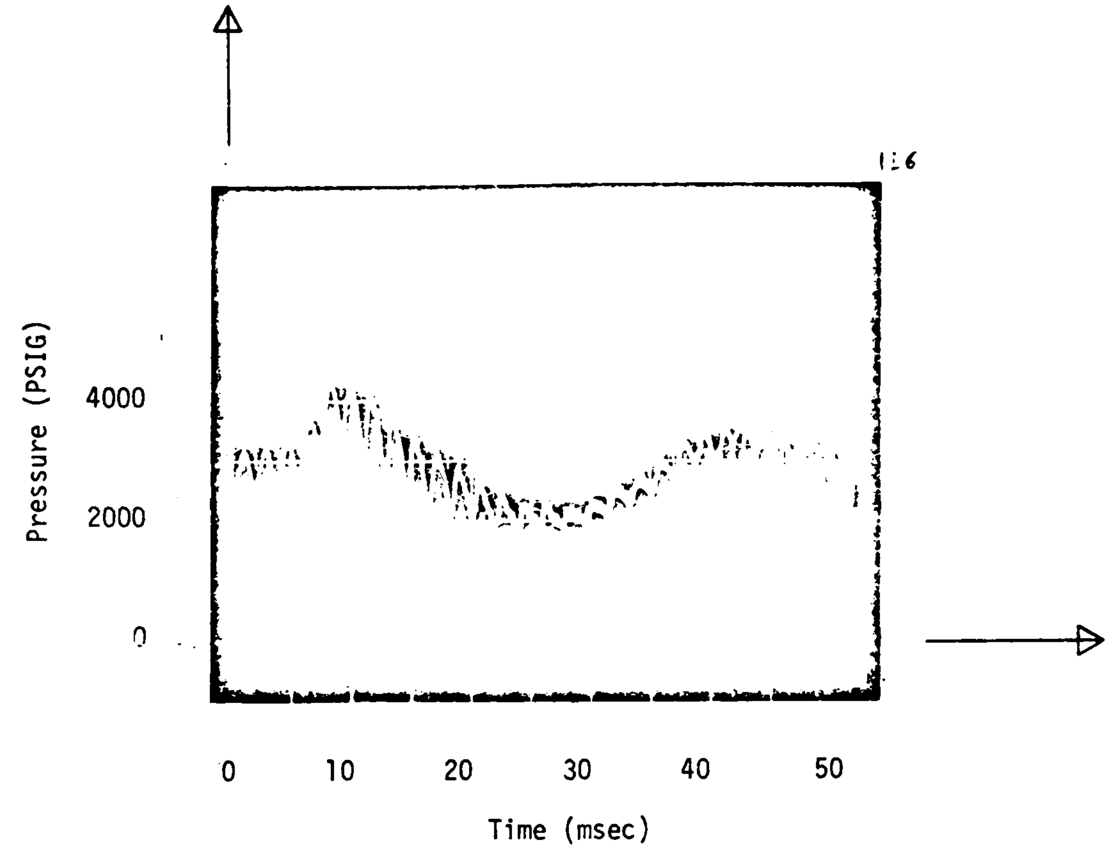


Fig 23. Transient Response, Pump System, Quincke-Tube (Short) Configuration, Taken at Point P5

In the HYTRAN computer program most of the errors came from inaccurate input data. The program itself is very accurate (as was proved by verification tests shown in Ref 6), especially when small time increments are specified for the solution by the method of characteristics. Most of the inaccuracies are components parameters needed for the programs. Some of those parameters are supplied in vendor catalogs, and some must be calculated from other data. It is recommended to verify experimentally every possible parameter to eliminate uncertainties. For example, the filter parameters were obtained as follows. The volume was measured by the amount of fluid it would hold. The pressure-flow coefficients were determined by applying a method of least-squares program to its given pressure-flow curve. It was not possible to check experimentally because the order of pressure readings was very small and needed more sensitive transducers.

The control valve pressure-flow characteristics were not available and were determined experimentally by matching the flow in the steady state part of the computer program to the flow measured in the experiment. The actual time of closing the valve has to be checked by special instrumentation of the valve in a special apparatus, which is very difficult. Instead it was checked by the pressure drop of P3 transducer, just downstream of the valve.

Another source of error was the internal leakage flow in the control valve. When the valve was closed to get a turn-off transient response, the flow rate did not come down to zero, but remained 1% of the flow rate with open valve. The computer program simulation was based on the flow rate dropping to zero. This contributed a 1% to the prediction error, as determined by computer runs.

In the correlation section the correlation between computer and experimental result was shown for a few configurations. The emphasis was on comparing the amplitudes of the transient pressure peaks (Figs 9 -11). However, there is a shift in the time scale of those curves, which is difficult to explain unless for some reason there is an error in the velocity of sound calculation in the computer program. An artificial correction of this time shift was made by changing the valve closing time in the computer program input, but the resulting transient pressure peak was 26% less than in the experiment (Fig 24). The conclusion is that this time shift may be neglected because only the amplitude and shape of the transient pressure peak (Fig 9) is important to the safety of the hydraulic system.

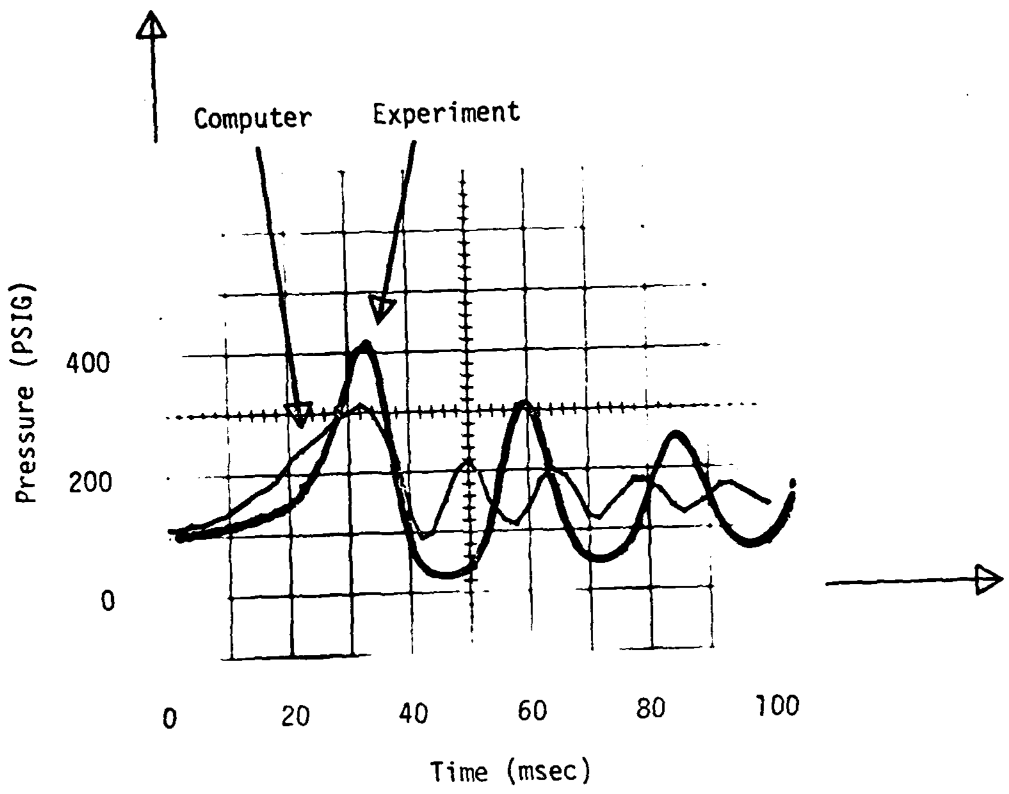


Fig 24. Correlation Between Experimental and Computer Results.
Reservoir System, Filter Configuration, 165 PSIA.
Attempt to Match Time-Scale.

IV. CONCLUSIONS

The HYTRAN computer program gave a very good prediction of the transient pressure peaks in both systems: 1% to 16% in the reservoir system and 7% to 20% in the pump system. This good prediction depends very much on accurate input data, which should be checked where possible. The most important input parameters were found to be the time of closing of the control valve which causes the transient response, and the steady state flow in the system calculated from all parameters that influence the system's impedance.

The effect of sharp-bends was found to be negligible in the transient response of the whole system, so there is no need to add to the program a special subroutine for sharp-bends.

The effect of filter was found to attenuate the amplitude of the transient pressure peaks and moderate rise time. In the pump system, the filter attenuated the pump ripple quite well.

The Quincke-Tube effect was different in the two test systems. In the reservoir system the response was almost the same for the straight line, the short Quincke-Tube (half wavelength) and the long Quincke-Tube (whole wavelength). In the pump system both Quincke-Tube configurations attenuated the transient pressure peak, but only the short one attenuated the pump ripple (as theory implies).

The HYTRAN computer program, together with the other programs in "Aircraft Hydraulic Systems Dynamic Analysis" package, is a very powerful design tool for the hydraulic systems engineers. It is concluded that there is a requirement for exact input parameters needed for the program.

Such available data would improve the accuracy of the program and make it more useful.

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APPENDIX

"HYTRAN" INPUT DATA

APPENDIX

HYTRAN INPUT DATA

The input data for the HYTRAN computer program was organized according to the HYTRAN user's manual (Ref 1). It is divided into five sections:

1. General control data.
2. Line data.
3. Component data.
4. System arrangement data.
5. Output requirement data.

The general control group set up the program title, time intervals, fluid temperature and type, number of lines and components and pressures. The fluid properties were obtained from tabulated data stored in the program.

The line data consists of the dimensions of the lines and modulus of elasticity.

The components data consists of a group of typical numbers for each component which describe its type, its connections, typical dimensions and operation parameters. Most of the components data was obtained from catalogs and talks with vendors. Some of it was checked experimentally, especially the control valve parameters that were doubtful.

The system arrangement data describes the way in which the components and lines are interconnected by designating nodes and describing the legs between nodes.

The output requirement data describes which output plots are desired. The line variables which can be selected are the pressures and flows (vs. time) calculated for each line point. A few component variables can also be plotted.

Two input data arrangements for the two experimental systems (Figs 1 and 6) are shown in Tables 3 and 4. For detailed explanation of these Tables refer to Ref 1.

```
***** DATA SIMPLE SYSTEM (FILTER) * **

THE TRANSIENT RESPONSE IS FROM T=0.0 TO T= .200 SECONDS AT TIME INTERVALS OF DEL = .00002
WITH OUTPUT POINTS PLOTTED AT INTERVALS OF , .00200 SECONDS

FLUID DATA FOR MIL-H-5606 AT 1000.0 PSIG, = 50.0 PSIG AND 75.0 DEG F IN 10.0 DEG F STEPS
        VISCOSITY     = [illegible]     [illegible] IN**2/SEC
        DENSITY       = [illegible]     [illegible] (LB*SEC**2)/IN**4
        BULK MODULUS  = [illegible]     [illegible] PSI
        VAPOUR PRESS. = [illegible] AT  75.0 DEG F
```

LINE DATA LINE NO.	LENGTH	INTERNAL DIA	WALL THICKNESS	MODULUS OF ELASTICITY	DELK	CHARACTERISTIC IMPEDANCE	VELOCITY OF SOUND
1	197.[illegible]	.3[illegible]	.035[illegible]	.300E+[illegible]	1.0[illegible]	[illegible]	5[illegible]
2	[illegible]	.30[illegible]	.0[illegible]	.3[illegible]	1.1536	[illegible]	[illegible]
3	[illegible]	.32[illegible]	.0[illegible]	.300E+[illegible]	1.0[illegible]	[illegible]	[illegible]
4	[illegible]	.4[illegible]	.0[illegible]	.300[illegible]	1.1250	35.5[illegible]	[illegible]

```
COMP,  1 INTEGER DATA   1 51  1 -1  [illegible]  0 0 0 0 0 0 0 0 0 0 0
REAL DATA CARD =  1  .1[illegible]E+03 0.  0.  0.  0.  0.  0.  0.
COMP,  2 INTEGER DATA   2 61  1  1 -2  0 0 0 0 0 0 0 0 0 0 0
REAL DATA CARD =  1  .3[illegible]E+01 .3[illegible]E+01 .1[illegible]E+00 .2[illegible]E-12 0.  0.  0.  0.
COMP,  3 INTEGER DATA   3 21  3  2 -3  0 0 0 0 0 0 0 0 0 0 0
REAL DATA CARD =  1  .[illegible]E-11 .5[illegible]E+00 0.  0.  0.  0.  0.  0.
REAL DATA CARD =  2  0.  .[illegible]E-02 .2[illegible]E-01 .2[illegible]E-01 .2000E+00 0.  0.  0.
REAL DATA CARD =  3  .2000E+00 .2[illegible]E+00 .2[illegible]E-11 0.  0.  0.  0.  0.
COMP,  4 INTEGER DATA   4 11  0  3 -  0 0 0 0 0 0 0 0 0 0 0
COMP, 10 INTEGER DATA   5 51  1  [illegible]  0 0 0 0 0 0 0 0 0 0 0
REAL DATA CARD =  1  .1[illegible]E+02 0.  0.  0.  0.  0.  0.  0.
    CPU TIME IN SECONDS =  1.[illegible]
```

TABLE 3. Example Input Data, Reservoir System, Filter Configuration, 165 PSIA

STEADY STATE INPUT DATA

NUMBER OF NODES = 4   NUMBER OF LEGS = 3   NUMBER OF CONSTANT PRESSURE NODES = 0

LEG CONNECTION INPUT DATA

LEG NO	UPST NODE NO	DNST NODE NO	NO OF ELEMENTS	FLOW GUESS	UPST PRESS	DNST PRESS
1	1	2	[illegible]	[illegible]	[illegible]	[illegible]
2	2	3	1	10.00000	[illegible]	[illegible]
3	3	[illegible]	[illegible]	10.00000	[illegible]	[illegible]

LEG NO	ELEMENTS IN LEG----
1	1 -- 1, 6 -- 1, 2 -- 1, 6 -- 2,
2	7 -- 1,
3	9 -- 3, 4 -- 1, [illegible] -- [illegible], 5 -- 1,

TABLE 3. (Continued) Example Input Data, Reservoir System, Filter Configuration, 165 PSIA

***** SECOND PUMP SYSTEM (QUINCKE TUBE) *****

THE TRANSIENT RESPONSE IS FROM T=0.0 TO T= .100 SECONDS AT TIME INTERVALS OF DELT= .00010

WITH OUTPUT POINTS PLOTTED AT INTERVALS OF .00100 SECONDS

FLUID DATA FOR MIL-H-5606 AT 3000.0 PSIG, - 50.0 PSIG AND 170.0 DEG F IN 10.0 DEG F STEPS

VISCOSITY - .[illegible]E-01 .[illegible]E-02IN**2/SEC

DENSITY - .[illegible]E-04 .7425-04 (LB-SEC**2)/IN**4

BULK MODULUS - .[illegible]E+06 .[illegible]E+06PSI

VAPOR PRESS.- .[illegible]E+01 AT 170.0 DEG F

LINE DATA LINE NO.	LENGTH	INTERNAL DIA	WALL THICKNESS	MODULUS OF ELASTICITY	DELX	CHARACTERISTIC IMPEDANCE	VELOCITY OF SOUND
1	50.0000	.3050	.0350	.300E+08	5.0000	[illegible]	47320.6[illegible]53
2	[illegible]	.2475	.0750	.300E+08	5.6250	57.5765	4[illegible].3223
3	[illegible]	.30[illegible]	.0350	.300E+08	5.0000	[illegible]	47920.[illegible]3
4	17.0000	.7200	.0[illegible]	.300E+08	5.0000	52.5722	47920.[illegible]3
5	14.0000	.7[illegible]	.0450	.300E+08	7.0000	52.5722	47920.6951
6	[illegible]	.2770	.0450	.300E+08	5.0000	[illegible].2433	4[illegible]731.1257
7	71.0000	.6700	.0050	.300E+08	5.0000	1[illegible].4035	47[illegible].7202
8	25.0000	.3050	.0350	.300E+08	5.2000	52.5722	47920.6[illegible]
9	5.0000	.7700	.0[illegible]50	.300E+08	5.0000	35.0752	4[illegible]325.4034
10	71.5000	.1440	.0250	.300E+08	5.1071	1[illegible].5453	4[illegible]158.9273

TABLE 4. Example Input Data, Pump System, Quincke-Tube (Short) Configuration

```
[illegible],   1  INTEGER DATA     1   51    4    7   -1   -5    0    0    0    0    0    0    0    0    0    0
REAL DATA CARD ?    1    .[illegible]E+04  .[illegible]E+07  .[illegible]E-01  .[illegible]E-01  0.            .3500E-02  .6500E+00  .6500E+0[illegible]
REAL DATA CARD ?    2    .[illegible]E+00  .2[illegible]E+03  .[illegible]E+02  .[illegible]E+02  .4400E+03  .2500E+03  .2[illegible]E-01  .2500E+02
REAL DATA CARD ?    3    .[illegible]E+01  .[illegible]      0.                .[illegible]70E-02  .2300E-02  .1000E-02  .2000E-01  .1800E+02
REAL DATA CARD ?    4    .[illegible]E+01  .[illegible]      .2[illegible]E-01  .[illegible]000E-01  0.            .9200E-02  .5930E+00  .5160E+0[illegible]
[illegible],   2  INTEGER DATA     2   11    0    1   -[illegible]  -10    0    0    0    0    0    0    0    0    0    0
[illegible],   3  INTEGER DATA     3   11    0    2   -[illegible]   10    0    0    0    0    0    0    0    0    0    0
[illegible],   4  INTEGER DATA     4   21    [illegible]    [illegible]   -[illegible]    0    0    0    0    0    0    0    0    5    0    0
REAL DATA CARD ?    1    .[illegible]E-01  .[illegible]E+0[illegible]  0.      0.      0.      0.      0.      0.
REAL DATA CARD ?    2    0.            .1[illegible]E-02  .[illegible]E-02  .5500E-02  .1000E+00  0.      0.      0.
REAL DATA CARD ?    3    .2[illegible]E+00  .2[illegible]E+00  .2[illegible]E-01  0.      0.      0.      0.      0.
[illegible],   5  INTEGER DATA     5   41    1    [illegible]   -[illegible]    0    0    0    0    0    0    0    0    0    0    0
REAL DATA CARD ?    1    .[illegible]E-01  .[illegible]E+00  0.      0.      0.      0.      0.      0.
[illegible],   6  INTEGER DATA     6   11    0    [illegible]   -[illegible]    0    0    0    0    0    0    0    0    0    0    0
[illegible],   7  INTEGER DATA     7   41    1    [illegible]   -[illegible]    [illegible]    0    0    0    0    0    0    0    0    0    0
REAL DATA CARD ?    1    .[illegible]E+0[illegible]  0.      0.      0.      0.      0.      0.      0.
[illegible],   8  INTEGER DATA     8   41    1    [illegible]   -[illegible]    0    0    0    0    0    0    0    0    0    0    0
REAL DATA CARD ?    1    .1[illegible]E+02  .1[illegible]E+02  .1[illegible]E+0[illegible]  .2000E-02  0.      0.      0.      0.
     CPU TIME IN SECONDS -     1.[illegible]
```

TABLE 4. (Continued) Example Input Data, Pump System, Quincke-Tube (Short) Configuration

STEADY STATE INPUT DATA

NUMBER OF NODES = 7 NUMBER OF LEGS = 9 NUMBER OF CONSTANT PRESSURE NODES = 0

LEG CONNECTION INPUT DATA

LEG NO	UPST NODE NO	DWST NODE NO	NO OF ELEMENTS	FLOW GUESS	UPST PRESS	DWST PRESS
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	10.[illegible]	0.[illegible]	0.[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	10.[illegible]	[illegible]	0.[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	10.[illegible]	0.[illegible]	0.[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	10.[illegible]	0.[illegible]	0.[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	10.[illegible]	0.[illegible]	0.[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	10.[illegible]	0.[illegible]	0.00000

LEG NO	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
7	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]

TABLE 4. (Continued) Example Input Data, Pump System, Quincke-Tube (Short) Configuration

VITA

Arie Zur was born [redacted]. He completed [redacted] in 1964. He studied in the "Technion" in Haifa, Israel through ROTC program, and graduated with a Bachelor of Science degree in Mechanical Engineering in 1968. He joined the Israel Air Force in November 1968 and was assigned to Air Force Headquarters, Research and Development Department, Aeronautical Design Branch. In this assignment he was responsible for designing and testing aircraft modifications. In June 1977 he entered the Air Force Institute of Technology for the Graduate Aeronautical Engineering program. He is married to [redacted] and they have [redacted]

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The transient response characteristics of two laboratory hydraulic systems, consisting of a simple reservoir system and a pump system, were obtained both experimentally and by simulation with a computer program called "HYTRAN". Influence of various hydraulic components such as bends, filters and pulsation-dampening devices (Quincke-Tube) was determined by testing various experimental configurations and predicting the transient response with the "HYTRAN" computer program.

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The correlation between computer and experimental results was quite good, especially in the simple reservoir system. Transient pressure peaks predicted by the computer program were within 20% of those obtained by experiment. The effect of sharp bends on system response was found to be negligible. Quincke-Tube influence and filter influence were found to attenuate both the pump ripple and the transient pressure peak. The transient response prediction of the "HYTRAN" program was found to be very sensitive to two input data parameters: the control valve closing time and the steady-state flow in the system.